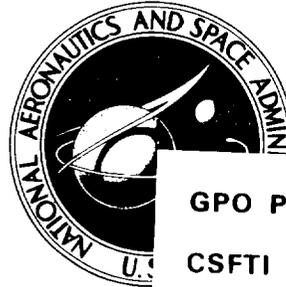


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# CRYOGENIC TEMPERATURE MEASUREMENT USING PLATINUM RESISTANCE THERMOMETERS

*by Donald H. Sinclair, Howard G. Terbeek,  
and Jerry H. Malone*

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Cleveland, Ohio*



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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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# CRYOGENIC TEMPERATURE MEASUREMENT USING PLATINUM RESISTANCE THERMOMETERS

by Donald H. Sinclair, Howard G. Terbeek, and Jerry H. Malone

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## SUMMARY

Results of evaluation tests on commercial platinum resistance thermometers (PRT) are reported. Three selective types of compact high-resistance PRT (1000 to 5000 ohms at 273.15° K) have proved to be stable, rugged, and sensitive. Resistance difference ratios as a function of temperature, called Z functions, conform closely with those of the high-quality standard PRT even in the nonlinear cryogenic range.

Fixed point calibrations at 273.15°, 77.40°, and 20.20° K plus interpolation between points by Z ratios yield probable uncertainties less than  $\pm 0.05^\circ$  K from 20° to 300° K. Also described are a calibration facility, cryostat, procedures for calibrating in liquid-hydrogen and liquid-nitrogen baths to  $\pm 0.02^\circ$  K, and instrumentation for field installations.

## INTRODUCTION

Evaluation tests of platinum resistance thermometers (PRT) were initiated at Lewis Research Center in order to satisfy the increasing demand for a reliable, accurate temperature sensor to measure cryogenic temperatures. PRT were selected mainly because of their commercial availability, reported stability and sensitivity (ref. 1).

Characteristics are well established for PRT which satisfy the National Bureau of Standards (NBS) qualifications for primary reference standard thermometers. Accuracy as a function of temperature, number of calibration points, and methods of interpolation between points is well documented (ref. 2). However, little has been reported on the quality of the commercial high-resistance PRT that have been developed during the past decade for applications outside the laboratory. For these field-type thermometers, calibration accuracy requirements are not as stringent as for the standard PRT. One-tenth °K is generally acceptable as compared with 0.01° K for experiments conducted in a laboratory.

The calibration of PRT involves relating the resistance of the transducer as a function of temperature. It is desirable to define this temperature function with as few and as convenient calibration points as possible. If all PRT have the same temperature-resistance function, the job of calibration is simplified.

The resistance-temperature function for pure, strain-free platinum above 90° K is expressed by the well known Callendar - Van Dusen equation

$$\frac{R_T}{R_0} = 1 + \alpha \left[ T - \delta \left( \frac{T}{100} - 1 \right) \left( \frac{T}{100} \right) - \beta \left( \frac{T}{100} - 1 \right) \left( \frac{T}{100} \right)^3 \right] \quad (1)$$

where  $R_T$  is the resistance of PRT at  $T$ ,  $R_0$  is the resistance at 0° C (273.15° K), and  $\alpha$ ,  $\delta$ , and  $\beta$  are constants obtained from measurements at specified temperatures. For temperatures above 0° C (273.15° K),  $\beta$  is zero (refs. 2 and 3).

Below 90° K the nonlinearity in the resistance-temperature (R-T) relations becomes much greater than at higher temperatures. And residual resistance (which is related to impurities, lattice defects, and strain) is increasingly more significant as temperature decreases (refs. 4 and 5). Therefore, attempts to extend the range of equation (1) below 90° K or to derive comparable expressions for relating resistance and temperature in the lower ranges have been unsuccessful (ref. 2). However, accurate calibrations from 20° to 273° K can be accomplished for PRT of proven quality with measurements at a minimum number of temperatures. This was demonstrated for primary reference standard PRT by Corruccini (ref. 3), who used R-T relations in terms of ratios of resistance differences,  $Z_T$  (Cragoe's function), which basically involve two measurements. Interpolation between the two base points is obtained from the relation

$$Z_T = \frac{R_T - R_{T,1}}{R_{T,2} - R_{T,1}} \quad (2)$$

where  $R_{T,1}$  and  $R_{T,2}$  are resistance values at base point temperatures  $T_1$  and  $T_2$ . The  $Z_T$  function simply expresses the fraction of the resistance span  $R_{T,1}$  to  $R_{T,2}$  which is realized in going from  $T_1$  to  $T$ . It, therefore, relates to temperature the percent of full-scale output of a bridge which measures resistance linearly from  $R_{T,1}$  to  $R_{T,2}$ . Then,

$$R_T = \frac{e_T}{e_{fs}} (R_{T,2} - R_{T,1}) + R_{T,1} \quad (3)$$

where  $e_T$  and  $e_{fs}$  are bridge-signal outputs at temperature  $T$  and at full scale. Hence,

$$\frac{e_T}{e_{fs}} = \frac{R_T - R_{T,1}}{R_{T,2} - R_{T,1}} = Z_T \quad (4)$$

Standard  $Z_T$  functions can be established from the resistance-temperature relation of a NBS calibrated primary reference standard PRT. Assuming that these standard  $Z_T$  functions apply equally to an unknown PRT,  $R_T$  values can be determined from known values of  $R_{T,1}$ ,  $R_{T,2}$  and the  $Z_T$  functions. The main objective of this investigation was to determine what errors would result from this assumption. To accomplish this objective,  $Z_T$  functions from multipoint calibrations of statistical samples of selected types of PRT were compared with the standard  $Z_T$  functions. These different types of PRT were compared for  $Z$  function agreement in three ranges with temperature base points as follows:

Resistance difference ratio	Temperature, °K	
	$T_1$	$T_2$
$Z_I$	20.20	77.40
$Z_{II}$	77.40	273.15
$Z_{III}$	4.20	20.20

Base point temperatures can be selected at or near the ends of any particular temperature range of interest. Those listed above were chosen because they were readily attainable. They represent the average local values of the helium, hydrogen, and nitrogen boiling points and the ice point. These  $Z$  functions satisfy our present needs. For other applications,  $Z$  tables based on other end points can be readily established from accurate calibration data for a primary reference standard PRT.

The equation (2)  $Z$  temperature function provides a means of conveniently solving two problems encountered when matching PRT. First, it normalizes PRT calibrations in terms of nondimensional resistance ratios. Therefore, it is not necessary to manufacture sensors whose absolute resistances are equal. Also, residual resistance which is not a function of temperature is canceled, because resistance differences are taken.

When Corruccini compared  $Z_T$  values based on  $T_1 = 20^\circ \text{K}$  and  $T_2 = 90^\circ \text{K}$ , the resulting average of maximum errors for 35 primary reference standard PRT did not exceed  $0.005^\circ \text{K}$ .

The investigation reported herein is a continuation of Corruccini's work. It extends

the application of two-point calibration with  $Z$  function interpolation to include some rugged, high-resistance, commercial PRT. And it proves that adequate accuracies can be obtained for three selected types of PRT if standard  $Z_T$  functions are applied from  $20^{\circ}$  to  $300^{\circ}$  K. Altogether 361 PRT were evaluated representing 16 types and six manufacturers. Sensor characteristics of reliability, repeatability, sensitivity, relative residual resistance, and self-heating were determined for each type of PRT.

To implement the investigation, a test facility was set up for performing accurate calibrations at temperatures from  $4^{\circ}$  to  $500^{\circ}$  K. Single-point calibrations were obtained in freely vented boiling cryogenic baths of liquid hydrogen, nitrogen, and helium. Temperatures between fixed points were obtained using Lewis built cryostats. Temperatures from  $230^{\circ}$  to  $500^{\circ}$  K were obtained in a controlled oil bath. All calibrations were made by comparison with thermometers which were calibrated by NBS. Resistances were measured by potential ratio comparison with stable, accurate reference resistors.

PRT instrumentation was designed suitable for field applications. The features of its design are included in this report.

## SYMBOLS

A	area
E	excitation voltage
$E_{\text{mon}}$	monitor excitation voltage
e	signal voltage
$\Delta e$	signal voltage error
$e_{\text{fs}}$	signal voltage at full scale
$e_{\text{H}}$	signal voltage at $T_{\text{H}}$
$e_{\text{L}}$	signal voltage at $T_{\text{L}}$
$e_{\text{mon}}$	monitor signal voltage
$e_{\text{r}}$	reference signal voltage
$e_{\text{s}}$	reference PRT signal voltage
$e_{\text{T}}$	signal voltage at T
$e_{\text{TC}}$	thermal signal voltage
$e_{\text{x}}$	signal voltage, unknown
I	current
K	thermal conductivity

$K_{Cu}$	thermal conductivity of copper
$K_{LHC}$	thermal conductivity of LHC alloy
$K_{SS}$	thermal conductivity of stainless steel
LHC	low heat conducting
R	resistance
$R_A, R_B, R_C, R_D$	PRT leads resistance
$R_{cal}$	bridge calibration resistance
$R_H$	PRT resistance at $T_H$
$R_i$	readout instrument input resistance
$R_L$	PRT resistance at $T_L$
$R_0$	resistance at $0^\circ C$
$R_r$	reference resistance
$R_s$	reference PRT resistance
$R_T$	resistance at T
$R_{T, 1}$	resistance at Z base point $T_1$
$R_{T, 2}$	resistance at Z base point $T_2$
$R_x$	unknown PRT resistance
$R_{Zero}$	bridge Zero resistance
$R_1, R_2, R_5, R_6$	bridge ends resistance
s	reference PRT
T	temperature
$\Delta T$	error or deviation in temperature
$T_H$	maximum measured temperature
$T_L$	minimum measured temperature
$T_1$	temperature at Z lower base point
$T_2$	temperature at Z upper base point
x	PRT, Test
Z	resistance difference ratio (Cragoe's function)
$Z_H$	Z at $T_H$
$Z_L$	Z at $T_L$

$Z_T$	Z at T
$Z_I$	Z with $T_1 = 20.20^\circ \text{ K}$ and $T_2 = 77.40^\circ \text{ K}$
$Z_{II}$	Z with $T_1 = 77.40^\circ \text{ K}$ and $T_2 = 273.15^\circ \text{ K}$
$Z_{III}$	Z with $T_1 = 4.20^\circ \text{ K}$ and $T_2 = 20.20^\circ \text{ K}$
$\alpha, \delta, \beta$	constants (Callendar-Van Dusen Equation)

## APPARATUS AND PROCEDURES

### Calibration Facility

Tests involved in this investigation were performed with the temperature calibration facility shown in the block diagram in figure 1. All major components required to calibrate temperature sensors are permanently connected to a program board switch. In preparation for the calibration of the temperature sensors, all circuit components are patchboard connected into the desired circuit. This arrangement allows for conducting a variety of calibration tests efficiently and with adequate accuracies by semiskilled operators.

Tests involving the use of liquid hydrogen as a coolant were conducted in a well ventilated area just outside the instrument laboratory. Precautions were taken to keep the hydrogen-to-air volume ratio below the 4-percent flammability limit by minimizing the boil-off rate of hydrogen and venting the area. Similar hydrogen testing at this instrument laboratory has been conducted in a routine manner for the past 10 years without mishap.

Multipoint calibrations. - Multipoint calibration of a statistical sample of PRT of a given type is necessary to determine whether two-point calibration with standard Z function interpolation is acceptable. Multipoint calibrations (from  $4^\circ$  to  $300^\circ \text{ K}$ ) are conducted in small, Lewis built cryostats as shown in figure 2. These cryostats employ principles of controlled heat transfer to provide a desired isothermal environment for calibrating PRT. The cryostat consists of two sealed concentric cylinders. A permanent heater block and a removable uniform temperature block are located within the inner cylinder. Sensors to be calibrated and one or more working standard thermometers are mounted in clearance holes in the uniform temperature block.

Before operation, the inner and outer cylinders are vacuum purged and filled with helium gas. During operation the assembly is immersed in a cryogenic coolant to a level well above the top of the outer cylinder. Coolants used are liquid nitrogen, hydrogen, or helium. The rate of heat transfer out of the inner cylinder is determined by setting the helium gas pressure in the conduction space between the cylinders. The rate of heat transfer into the inner cylinder is determined by the amount of electrical power supplied to a heater wrapped around the heater block. When the rate of heat removal to the coolant is balanced by a minimum of heat supplied by the control heater a stable calibration temperature exists within the inner cylinder. Control sensors are placed in the heater block to enable automatic temperature control. A PRT is used for control from 20<sup>0</sup> to 300<sup>0</sup> K and a germanium resistance thermometer from 4<sup>0</sup> to 20<sup>0</sup> K.

The heat leak down the support tube and instrument lead wires to the inner cylinder is minimized by using low-heat-conducting (LHC) alloy wires and thin-wall stainless-steel tubing. Within the inner cylinder these permanent interconnect leads are heat sunk to the permanent heater block before being terminated. Also, to decrease the conductive heat path from the heater block to each sensor, all sensor leads are made of LHC alloy and heat sunk to the uniform temperature sensor mounting block.

To improve the thermal equilibrium between sensors, a helium gas pressure greater than 1 psia (7 kN/m<sup>2</sup>) is maintained within the inner cylinder. Also, aluminum-foil packing is carefully added around the sensors to reduce the thermal impedance from the sensor to the uniform temperature block. Before data are recorded, the signal from an individual test sensor is monitored for at least 10 minutes to ensure that its temperature is stable within ±0.01<sup>0</sup> K. Despite this extreme care to minimize the temperature gradients between sensors, gradients do exist. This is considered the largest source of error in our experiment and at times amounts to about 0.03<sup>0</sup> K.

Bath calibrations. - Boiling baths of liquid hydrogen, nitrogen, and, sometimes, helium are used to point-calibrate PRT at 20.20<sup>0</sup>, 77.40<sup>0</sup>, and 4.20<sup>0</sup> K, respectively. These liquids are contained in well insulated metal Dewars. The Dewars are vented such that the ullage pressure equals the local barometric pressure within ±0.1 inch (±0.254 cm) of water. After loading the Dewar with liquid, at least 1 hour is allowed for the system to come to thermal equilibrium before calibration data are taken. When necessary, the temperature of the bath is measured with a standard thermometer which has been calibrated by NBS. The saturation temperature corresponding to the barometric pressure is not used. The temperature at the liquid-gas interface agrees with published values of saturation temperature (refs. 6 and 7); however, the bulk of the bath is superheated. For

liquid nitrogen, the main bath temperature is uniform to within  $\pm 0.01^\circ$  K but superheated by  $0.1^\circ$  to  $0.5^\circ$  K. Liquid-hydrogen uniformity is within  $\pm 0.002^\circ$  K and superheated by  $0.01^\circ$  to  $0.05^\circ$  K.

The amount of superheating depends on the physical properties, magnitude of heat flux, and bath agitation of the coolant. Because of the surface tension of the fluid, the bubbles in the bath are at a pressure greater than the fluid pressure. This causes the bath temperature to be higher than the saturation temperature which does exist at the surface of the fluid (ref. 8). For a nonagitated boiling bath, a sharp temperature gradient exists within 2.5 millimeters below the liquid-to-gas surface. With increased agitation, the amount of superheating decreases, and the surface temperature gradient extends farther into the bath.

The advantages of bath calibrations as opposed to cryostat calibrations are as follows:

- (1) Time for preparation and taking data is measured in hours compared with days for cryostat calibrations. Also, more sensors can be calibrated at one time in a bath.
- (2) Better accuracies are obtainable: This is principally due to the lower temperature gradients between sensors in a bath as compared with those in a cryostat.

Calibration resistance measurement. - Resistance thermometers are calibrated using a potential ratio circuit where the unknown PRT resistance  $R_x$  is compared with a known reference resistance  $R_r$  in a series circuit.

$$R_x = \frac{e_x}{e_r} R_r \quad (5)$$

where  $e_x$  and  $e_r$  are the measured voltage drops across  $R_x$  and  $R_r$ .

Figure 3 shows a typical circuit connected for production calibration of PRT. It features a constant current power supply and up to 20 channels of automatic potential switching with digital printed output. As many as 18 PRT are placed within the uniform temperature environment. Sensors  $s_1$  and  $s_2$  are reference PRT which have been previously calibrated by careful comparison with an NBS calibrated primary reference standard PRT.

At any stable temperature close to the desired calibration temperature, the calibration resistance of a test sensor  $R_{x,n}$  is determined by comparing its voltage drop  $e_{x,n}$  to that of the reference PRT,  $e_{s,1}$ .

$$R_{x, n} = \frac{e_{x, n}}{e_{s, 1}} R_{s, 1} \quad (6)$$

where  $R_{s, 1}$  is the known resistance of  $s_1$  at the desired calibration temperature. The exact temperature of the environment is not critical as long as all sensors (s and x) are at the same uniform temperature and have approximately the same sensitivity  $\partial R / (R \partial T)$ . This method of comparing PRT achieves accurate and efficient production calibration.

The second reference PRT  $s_2$  is redundant and is used to check the temperature uniformity of the calibration environment and calibration stability of reference PRT  $s_1$  by

$$\frac{R_{s, 1}}{R_{s, 2}} = \frac{e_{s, 1}}{e_{s, 2}} \quad (7)$$

Also, resistors  $R_{r, 1}$  and  $R_{r, 2}$  are accurately known stable reference resistors. They are used to check the resistance measurement accuracy of the calibration by

$$\frac{R_{r, 1}}{R_{r, 2}} = \frac{e_{r, 1}}{e_{r, 2}} \quad (8)$$

These checks must be within the required calibration accuracy before the calibration data are acceptable. A typical PRT sensitivity plot as shown in figure 4 is helpful when determining the required resistance measurement accuracy for a desired temperature accuracy. For example, if a calibration error is limited to  $\pm 0.02^\circ \text{K}$  ( $\Delta T$ ), the necessary resistance measurement uncertainty at  $20^\circ \text{K}$  must not exceed

$$100 \frac{\Delta R}{R_{20}} = \frac{100}{R_{20}} \frac{\partial R}{\partial T} \Delta T = \left( \frac{14\%}{^\circ \text{K}} \right) (0.02^\circ \text{K}) = 0.28\% \quad (9)$$

while the required uncertainty at  $77^\circ \text{K}$  would have to be better than

$$100 \frac{\Delta R}{R_{77}} = \frac{100}{R_{77}} \frac{\partial R}{\partial T} \Delta T = \left( \frac{2.3\%}{^\circ \text{K}} \right) (0.02^\circ \text{K}) = 0.046\% \quad (10)$$

Resistance measurement uncertainties as low as  $\pm 0.01$  percent are obtainable from the digital voltmeter readout circuit shown in figure 3. When uncertainties better than

0.01 percent are required, the precision six-dial potentiometer is used to measure the voltage ratios.

Some other advantages of a potential ratio resistance measuring circuit are as follows:

(1) Lead wire resistances are negligible, and a true four-terminal resistance measurement is made.

(2) Circuit thermals are easily canceled by either (a) averaging signal voltage measurements with current flowing in opposite directions or (b) measuring the thermals with the current off and algebraically deducting their values from the current-on signal voltage measurement.

(3) Accurate absolute signal voltage measurements are not required because voltage ratios are taken.

(4) PRT can be easily matched because many PRT can be simultaneously calibrated, and the same instrumentation is used for all like calibrations.

(5) Versatile ranges of resistance, current, voltage amplification, etc., are easily obtainable.

## INSTRUMENTATION FOR FIELD INSTALLATIONS

Temperature measurement using PRT involves converting temperature-related resistance of the PRT to a suitable electrical signal at a signal conditioner. In the interest of accuracy and reliable performance of these measurements, Lewis has standardized a PRT and signal conditioner which will be discussed. This standardization has been a direct result of this reported effort.

Instrumentation standardization has many advantages, such as

- (1) Predictable accuracy and reliable performance.
- (2) Uniform data reduction.
- (3) Uniform specifications, acceptance testing, calibration.
- (4) Uniform installation and operation.
- (5) Decrease in cost.

## Transducer

The varied requirements for cryogenic thermometry at Lewis are best met by storing calibrated sensors which can be quickly assembled into a desired probe shape or else installed directly into the test rig. The assembly and installation must be accomplished with no change in calibration. A PRT that meets these requirements is shown in figure 5.

Its dimensions are such that it can be assembled by sweating the sensor 0.145-inch (3.68-mm) outside diameter shoulder into a standard 3/16-inch (4.8-mm) outside diameter by 0.02-inch (0.5-mm) wall tube, of any desired length, to form a probe. Probe construction including electrical connector and pressure fittings normally takes less than 2 hours to complete. In other installations the sensor can be sweated directly into a clearance hole in the rig. For corrosive applications where a sealed probe is required, a suitable split pin can be fitted into the 0.10-inch (2.54-mm) inside diameter of the sensor to enhance thermal conduction between sensing element and probe. A similar split pin will allow the sensor to be wall mounted.

This PRT also has the following desirable qualities:

- (1) 1000-ohm resistance at the ice point and an appreciable  $\partial R/\partial T$  sensitivity at low temperatures.
- (2) Stability better than  $\pm 0.02^\circ \text{K}$ .
- (3) Ruggedness.
  - (a) 50 g's or 0.5-inch (12.7 mm) double amplitude (whichever is smaller) from 20 to 2000 hertz for 15 minutes.
  - (b) Impact shock of 100 g's for 10 milliseconds triangular wave.
  - (c) Velocity loading greater than 30 feet per second (9 m/sec) of water flow.
  - (d) 2000 psi (1.4 MN/m<sup>2</sup>) pressure differential with less than  $10^{-7}$  cubic centimeter helium per second leak rate.
- (4) Time response of 0.1 second for  $10^\circ \text{K}$  temperature changes in water flowing at 3 feet per second (0.9 m/sec) and 0.03 second in liquid hydrogen at the same rate of flow.
- (5) Conformance to standard  $Z_T$  functions to within  $\pm 0.05^\circ \text{K}$  from  $20^\circ$  to  $300^\circ \text{K}$ .
- (6) High platinum purity and virtually stress free construction. For example, at  $20^\circ \text{K}$  the resistance is less than 0.005 times its resistance at the ice point and its sensitivity is greater than 14 percent per  $^\circ \text{K}$ .
- (7) Self-heating, in quiescent liquid nitrogen less than  $0.03^\circ \text{K}$  per milliwatt.

Four leads are attached to the sensor to allow line resistance to be minimized by potential ratio or multiple bridge measuring circuitry. To decrease the lead wire heat conduction to the sensor, LHC alloy leads are used where cryogenic temperature gradients exist along the sensors leads. Copper leads should be avoided because they will carry considerably more heat than LHC alloy leads. Table I compares the thermal conductivity of copper  $K_{\text{Cu}}$  to LHC alloy  $K_{\text{LHC}}$  for three temperature conditions. The table also demonstrates that the area-thermal conductivity product of four 28-gage copper leads  $(AK)_{\text{Cu}}$  is greater than that of a 3/16-inch (4.8-mm) outside diameter by 0.02-inch (0.5-mm) wall stainless-steel tube  $(AK)_{\text{SS}}$ . The values given in the table assume no radial heat loss.

TABLE I. - TYPICAL HEAT CONDUCTION COMPARISON

Copper leads to -	End temperatures, T, °K		
	20 to 35	20 to 90	20 to 300
LHC alloy leads, $K_{Cu}/K_{LHC}$	195	65	25
Stainless-steel tube, $(AK)_{Cu}/(AK)_{SS}$	36	10	3

### Signal Conditioner

A potential ratio circuit as described above and shown in figure 3 is useful for calibrating PRT in that it affords a convenient means of measuring resistances of a number of sensors in a series circuit. Uncertainties are on the order of 0.005 to 0.1 percent of resistance depending on the quality of the instruments used and the techniques employed in making measurements. The advantages of this system are elaborated in the section CALIBRATION RESISTANCE MEASUREMENT. The same type of system can be used for measuring temperatures in field applications. It requires, however, that the resistance of every sensor (PRT) be converted to temperature from its own individual calibration. The inconvenience of this method can be overcome by providing a separate bridge type signal conditioning circuit for each PRT. By matching the bridge circuit to the sensor calibration for a given range of temperature, the signal output as a function of temperature can be normalized by applying Z functions.

$$\frac{e_T}{e_{fs}} = \frac{Z_T - Z_L}{Z_H - Z_L} \quad (11)$$

where  $Z_L$  is equal to Z at the minimum temperature to be measured  $T_L$  and  $Z_H$  is equal to Z at the maximum temperature to be measured  $T_H$ . One calibration ( $e/e_{fs}$ ) as a function of T then applies for all sensors of proven quality having the same temperature range. An additional advantage of the bridge circuit is that signal voltage e is limited only to resistance in the range of interest.

A versatile bridge type signal conditioner suitable for PRT is being procured competitively to Lewis specifications. It is in the form of a module which plugs into an eight-channel case mounted in a relay rack cabinet. The module features an isolated, regulated direct-current power supply with output adjustable from 10 to 30 volts. An array of terminals is provided on a circuit board for mounting resistors composing a bridge network.

Selection of resistors is dictated by the PRT calibration, range of temperature, and desired range of output voltage signal  $e$ .

A circuit diagram is shown in figure 6. Resistor  $R_{Zero}$ , opposite the PRT, establishes a potential to which the PRT potential is referred. The bridge output signal  $e$  then becomes a measure of the departure of the PRT resistance from the reference value. Bridge excitation voltage  $E$  is adjustable to obtain a desired span of output signal for the range of resistance (temperature) to be measured.

The bridge proper also includes end resistors  $R_1$ ,  $R_2$ ,  $R_5$ , and  $R_6$  which are generally from 25 to 200 kilohms. A large resistance at  $R_6$  compared with a relatively small resistance change experienced by the PRT in the range of measurement results in a virtually constant current through the PRT. The total change in current is a function of  $(R_H - R_L)/R_6$  where  $R_L$  is the PRT resistance at  $T_L$  and  $R_H$  is the PRT resistance at  $T_H$ .

It can be shown from circuit analysis that large end resistances minimize effects of lead resistance (ref. 9). Output signal errors of 0.02 percent or less are realized with lead resistances  $R_A$  and  $R_B$  unbalanced as much as 10 ohms. Lead resistance  $R_D$  will influence the current through the sensor by a factor  $R_D/R_6$ . However,  $R_D$  seldom exceeds 3 ohms and, hence, is negligible. When  $R_D$  is large, its effect can be compensated during bridge setup. Effects of lead resistance  $R_C$  are negligible when in series with a high-impedance readout instrument.

Relays operated at the module or by remote control provide the following functions:

- (1) Zero - De-energizes the bridge circuit so that thermal electromotive force  $e_{TC}$  can be measured. Power supply output is transferred to a nominal load to hold the circuit in an operating standby condition.
- (2) Calibrate - Substitutes a fixed resistor  $R_{cal}$  into the circuit in place of the PRT; the resulting output  $e$  verifies zero and span settings.
- (3) Monitor - Allows measurement of excitation voltage  $E_{mon}$  and bridge signal  $e_{mon}$ .

Normal setup procedure is to first select a calibrated PRT and have it assembled into a probe suitable for the required installation. From the PRT calibration,  $R_{T,1}$  and  $R_{T,2}$  are established.  $R_L$  and  $R_H$  are calculated using standard Z functions.

$$R_L = R_{T,1} + Z_L (R_{T,2} - R_{T,1}) \quad (12)$$

$$R_H = R_{T,1} + Z_H (R_{T,2} - R_{T,1}) \quad (13)$$

Approximate sensor current  $I$  is determined from the relation

$$I = \frac{e_H - e_L}{R_H - R_L} \quad (14)$$

where  $e_L$  and  $e_H$  are the bridge output signals at  $T_L$  and  $T_H$ , respectively;  $e_L$  is usually equal to zero. Consideration of thermal resistance characteristics of the sensor and the rate of heat transfer for the measurement application will provide an estimate of what errors can be expected from electrical self-heating (Joule effect). Normally ample signal can be obtained with negligible self-heating. A resistance value for the end resistors  $R_1$ ,  $R_2$ ,  $R_5$ , and  $R_6$  approximately equal to  $E/2I$  is then selected. These four end resistors are installed at appropriate terminals on the module circuit board. Resistor  $R_1$  should match  $R_2$ , and  $R_5$  should match  $R_6$  to within 1 percent. The temperature coefficients of all resistors except the 50 kilohms load resistor are less than 25 ppm per  $^{\circ}\text{K}$ . Before making zero and span adjustments, resistances approximately equal to the field installation values of  $R_A$ ,  $R_B$ , and  $R_D$  are inserted in the bridge setup circuit.

For zero adjustment, a resistance equal to  $R_L$  is connected to the bridge terminals in lieu of the PRT. The  $R_{\text{Zero}}$  bridge resistor is trimmed as required to obtain  $e_L$ . The PRT substitute resistance then is increased to the  $R_H$  value, and  $E$ , the excitation voltage, is adjusted to obtain  $e_H$ . Then the calibration resistor  $R_{\text{cal}}$  which is slightly less than  $R_H$ , is substituted for the PRT, and the calibration output signal is measured and recorded. Thereafter, the signal conditioner output will respond as in equation (11). Finally, the setup adjustments are verified by connecting the bridge and PRT together and measuring the output with the PRT at a convenient known temperature.

Because the PRT and its signal conditioner have excellent stability, all necessary adjustments are made in a laboratory environment. And no further adjustment is required in the field. However, faulty installation and component failures can be detected by the zero, monitor, and calibrate checkout capability of the signal conditioner. Therefore, a high degree of measurement reliability is obtained.

## Predicting Field Measurement Accuracy

A practical error analysis for a PRT temperature measurement system can be made by considering all possible sources of error and then concentrating on those errors which are most significant relative to required accuracy. A critical analysis of many of these errors demands a knowledge of the theory and principles of thermophysics. However, an acceptable order of magnitude of individual errors can be determined by extrapolating experimental data along with educated assumptions and simplified theory (refs. 8 and 10).

Sources of error to be considered in field measurement are listed together with some helpful hints.

(1) Readout measurement - The error involved in measuring the bridge output  $e$  is usually the largest, its magnitude depending on the quality of the readout instrument. Although  $e$  is directly proportional to change in PRT resistance, the resistance is nonlinear with respect to temperature, especially below  $70^{\circ}$  K (see figs. 7 and 8). Hence, a constant error in signal  $\Delta e$  will result in a nonlinear temperature error. Figure 9 shows plots of temperature errors corresponding to an error of 0.1 percent of the full-scale signal  $e_{fs}$  for five typical temperature spans. Equivalent temperature errors  $\Delta T$  can be determined for other measured signal errors  $\Delta e/e_{fs}$  and temperature spans  $T_H - T_L$  using the data from figures 7 and 8.

$$\Delta T = \frac{\Delta e}{e_{fs}} \left( \frac{Z_H - Z_L}{\frac{\partial Z}{\partial T}} \right) \quad (15)$$

Notice that temperature readout errors will be about constant for temperatures greater than  $70^{\circ}$  K, because  $\partial Z/\partial T$  is approximately constant. Also, decreasing the temperature span will decrease the temperature readout error. However, a practical limit is reached when the readout error is less than the PRT calibration error.

(2) Calibration error - For PRT of a type whose quality has been proven adequate by multipoint calibration of a statistical sample of like sensors, the error is less than  $\pm 0.05^{\circ}$  K from  $20^{\circ}$  to  $300^{\circ}$  K. This error limit applies when the sensor has been calibrated correctly ( $\pm 0.02^{\circ}$  K) at three points, for example,  $20.20^{\circ}$ ,  $77.40^{\circ}$  and  $273.15^{\circ}$  K, with intermediate values interpolated by  $Z$  functions.

(3) Thermal electromotive force - Thermals are 20 microvolts or less when the circuit is thermoelectrically balanced, that is, when like metals (leads) are exposed to the same thermal gradients and corresponding junctions are at equal temperatures. This error is minimized when the signal output  $e_{fs}$  is increased and alloy wires with low thermoelectric power are used. It can be compensated by measuring  $e_{TC}$  and algebraically deducting it from the measured signal  $e$ .

(4) Electrical hum - Hum is 20 microvolts or less with twisted leads, proper shielding and grounding; 60-hertz hum is usually most troublesome. The error can be reduced when impedance is kept low and signal output  $e_{fs}$  is increased.

(5) Line resistances - Errors are negligible provided instrumentation equivalent to that outlined in figure 6 is used with Line A matching Line B in resistance to within 10 ohms, and the field installation resistance of Line D is known to within 3 ohms.

(6) Stability - Signal conditioner supply voltage  $E$  and bridge resistors are stable to better than 0.1 percent. And stability can be checked in the field with the calibration

signal. Signal conditioner set-up will compensate for any change in sensor current caused by the PRT resistance change from  $R_L$  to  $R_H$ .

(7) Circuit loading - A signal readout instrument with a low (less than 1 megohm) input impedance  $R_i$  will decrease the calibrated output of the signal conditioner by less than  $(R_H/R_i)e$ . However, this would result in a low calibration signal for which a proportional data correction could be applied. Or else the low calibration signal could be compensated by an increase in the  $E$  adjustment.

(8) Stem conduction - Error from heat conducted along the probe depends on many variable factors including the heat transfer to the medium to be measured, the length of leads and probe, and the gradient between the probe support and the sensor. Use of thin-wall stainless-steel probe and LHC alloy leads (rather than copper) through the gradient reduces thermal conduction error (see table I). For figure 5 probes (not sealed) whose immersion lengths are greater than 3 inches (75 mm), conduction errors are less than  $0.05^\circ\text{K}$  for liquid-hydrogen applications.

(9) Sensor size - Size can introduce an error if the temperature to be measured is highly localized. The PRT tends to sense an average temperature over the surfaces adjacent to the sensing element. The size of the figure 5 PR sensor, 0.14 inch (3.5 mm) diameter by 0.5 inch (13 mm) long, is a disadvantage. The sensor could be made smaller. However, any significant reduction in size may require less resistance or a compromise in quality and reliability.

(10) Response time - The time constant for the specified PRT (fig. 5) with a small step change in temperature is on the order of 0.1 second or less, particularly at low temperatures where the specific heats of most media approach zero. Accurate prediction of the transient performance of a PRT is difficult to determine (ref. 11). The best method of determining approximate response time in a given application is by comparing the rate of change of the PRT with that of a small thermocouple installed close to it.

(11) Self heating - This is usually less than  $0.1^\circ\text{K}$  per milliwatt in quiescent liquid nitrogen. To establish the error factor for other conditions, it is necessary either to multiply by the ratio of the heat-transfer coefficients or else to determine it experimentally. Because most applications require power levels less than 0.1 milliwatt, this error is usually negligible.

Of all the sources of error, experience has shown that only the first two, readout measurement and calibration, are of primary importance. Generally, the others are of little or no consequence, and rough calculations are adequate to prove this.

# RESULTS

## Sensors Evaluated

Table II lists some of the characteristics of the PRT evaluated. Initially, PRT types 1 to 12 were subjected to various tests, mainly to establish the general quality of commercial PRT at cryogenic temperatures. These tests determined the reliability, repeatability, sensitivity, relative residual resistance, and self-heating in liquid nitrogen for each type of PRT. Other factors such as size, ease of installation, and cost were considered. Thirty-eight PRT from five manufacturers were tested.

Compromises were then made between optimum measurement requirements and the manufacturing state-of-the-art. This enabled Lewis to obtain two similar PRT, types A-13 and A-14. Fifty-one of each type PRT were procured. These PRT satisfied performance requirements, but installation difficulties became apparent. Further improvement led to PRT type A-15 (see fig. 5) which is presently being procured competitively to Lewis specifications and meets most requirements. Its main limitation is its size.

Table II also lists the nominal characteristics for a type P-S PRT which meets NBS qualifications for a primary reference standard thermometer. Type F-16 was included to show the characteristics of a poor quality PRT.

Reliability. - Our experience with PRT indicates that, in general, the reliability of commercial PRT is poor. Twelve of the initial 38 PRT tested failed. A PRT was considered to have failed when it lost continuity or broke and could not be repaired externally. Failures usually occurred during thermal shocking and while preparing for tests with reasonable handling procedures. Notice that 3 out of the 7 standard thermometers, type P-S, failed even though special precautions were taken with these PRT. Failure was attributed to the fragile lead seal on the type P-S PRT.

Failure rate was not a function of cost or supplier. However, certain types of PRT such as A-13, A-14, and A-15 demonstrated excellent reliability. Only one failure out of the 304 total has occurred during evaluation testing and field usage of these PRT.

Sensitivity. - Sensitivity of PRT is ample for temperature measurements of high accuracy. For example, at liquid-hydrogen temperatures, the high  $\partial R/\partial T$  for types A-13, A-14, and A-15 will allow output signals greater than 1 millivolt per  $^{\circ}\text{K}$  with less than 10 microwatts of power being supplied to the PRT. Sensitivity expressed as  $\partial R/(R \partial T)$  is of particular interest when establishing the resistance measurement accuracy required to achieve a desired temperature accuracy. This was previously discussed with reference to figure 4. Also, this sensitivity or a resistance ratio such as  $R_{20}/R_{77}$  provides a figure-of-merit which indicates relative quality, platinum purity, and stress freedom. Notice that PRT types A-13, A-14, and A-15 closely approach the quality of the standard thermometer type P-S.

TABLE II. - COMPARISON OF PLATINUM RESISTANCE THERMOMETERS<sup>a</sup>

Manufac- turer	Type	Reliability		Temperature, T, °K						Residual ratio, R <sub>20</sub> /R <sub>77</sub> , percent	Repeatability at 20° K, ± °K	Self-heating in liquid nitrogen, °K/mW	Cost, dollars		
		Tested	Failed	273	Resistance, R, ohm			Sensitivity							
					77.4	20.2	77	20	20					∂R/∂T, ohm/°K	∂R/(R∂T), %/°K
					945	25.5	21.6	3.8	14.8						
A	1	3	0	5000	945	25.5	21.6	3.8	14.8	2.7	0.01	0.02	190		
A	2	3	2	200	38.2	.96	.87	.15	15.6	2.5	→	.04	100		
A	3	3	2	500	95	2.97	2.1	.38	12.8	3.1		.07	80		
B	4	3	0	1340	260	18	5.8	1.0	5.6	6.9		.02	280		
B	5	3	0	500	94.5	2.55	2.1	.38	14.8	2.7		.02	140		
B	6	5	1	435	83	2.5	1.9	.33	13.2	3.0		.01	40		
C	7	3	2	4770	925	51.5	20.5	3.7	7.2	5.6		.01	350		
C	8	3	1	500	96	4.17	2.1	.38	9.1	4.3		.02	190		
C	9	3	1	455	90	7.28	2.0	.35	4.8	8.1		.11	120		
D	10	3	0	100	19.8	1.5	.43	.077	5.1	7.6		.01	20		
E	11	3	1	335	63.3	1.66	1.45	.26	15.7	2.6		.07	330		
E	12	3	2	183	35	.85	.79	.14	16.5	2.4		.04	180		
A	13	51	0	5000	945	25.5	21.6	3.8	14.8	2.7		.02	190		
A	14	51	0	1380	261	6.6	5.9	1.04	15.7	2.5		.02	170		
A	15	202	1	1000	189	4.86	4.3	.74	15.2	2.6		.03	140		
F	16	19	8	335	64	5.0	1.4	.26	5.2	7.8		.05	50		
P	S	7	3	25.5	4.81	.11	.11	.019	17.3	2.29		.02	450		

<sup>a</sup>Nominal values.

Self-heating. - PRT self-heating normally causes negligible measurement error. However, the magnitude of error should be checked, preferably under heat-transfer conditions encountered during operation. Self-heating is defined as that increase in sensor temperature above the temperature of the measured medium where the increase is caused by the electrical energizing power of the sensor. The magnitude of self-heating error depends on the PRT construction and the medium in which the PRT is immersed while measurements are taken. The self-heating ( $^{\circ}\text{K}/\text{mW}$ ) was determined for all types of PRT in the same medium. The medium was nonagitated boiling liquid nitrogen. Figure 10 shows typical experimental results. Plotted is the maximum self-heating temperature rise for five type A-15 PRT at various power levels. The slope of this curve is  $0.03^{\circ}\text{K}$  per milliwatt. For different media this self-heating value would change. For liquid hydrogen, it would increase to about  $0.1^{\circ}\text{K}$  per milliwatt. The power levels used to obtain this self-heating data are beyond normal operating levels. Normally, power levels do not exceed 0.1 milliwatt at liquid-nitrogen temperatures. For PRT type A-15, 0.01 milliwatt is usually adequate and would cause  $0.0003^{\circ}\text{K}$  negligible self-heating error in nonagitated liquid nitrogen.

Repeatability. - If a PRT is to hold its calibration it must have good repeatability. And, in general, the PRT tested had excellent repeatability. All sensors except types E-12 and F-16 had repeatable calibrations at  $20.20^{\circ}\text{K}$  to within an instrumentation uncertainty of  $\pm 0.01^{\circ}\text{K}$ . These data include at least five calibrations with thermal cycling from  $300^{\circ}$  to  $20^{\circ}\text{K}$  between calibrations. Figure 11 shows typical repeatability data for a standard PRT (type P-S) at the triple point of water ( $273.16^{\circ}\text{K}$ ), in liquid nitrogen ( $77.40^{\circ}\text{K}$ ) and in liquid hydrogen ( $20.20^{\circ}\text{K}$ ). All calibrations were referred to NBS calibration at time zero. The nitrogen and hydrogen data, taken 16 months after the NBS calibration, were obtained using our production calibration system with an uncertainty of  $\pm 0.01^{\circ}\text{K}$ . Other data were obtained with our precision instrumentation with an uncertainty of  $\pm 0.005^{\circ}\text{K}$ .

Figure 12 shows that field type PRT can hold their calibrations over extended periods of time. Presented are differences in calibration at  $20.20^{\circ}\text{K}$  of a type A-1 PRT referred to its initial calibration. The data include 12 calibrations over a 2-year span. The manufacturer's calibration at  $20.20^{\circ}\text{K}$  was found to be in error by  $+0.09^{\circ}\text{K}$ . The manufacturer presented a lower value of resistance for  $20.20^{\circ}\text{K}$ . This error was attributed to the fact that calibrated values in the hydrogen range were obtained by incorrect interpolation from calibrations in helium and nitrogen.

### Matching PRT - Z Temperature Functions

Z<sub>1</sub> Matching,  $T_1 = 20.20^{\circ}\text{K}$ ,  $T_2 = 77.40^{\circ}\text{K}$ . - Figure 13 shows the matching of seven standard quality type P-S PRT using NBS calibration data. The maximum deviation

for all seven PRT from their average  $Z_I$  function was within  $\pm 0.005^\circ$  K from  $18^\circ$  to  $92^\circ$  K. This  $\pm 0.005^\circ$  K deviation is a negligible error when field measurement accuracy requirements of  $\pm 0.1^\circ$  K are considered. Therefore, the data for any one of the seven standard type P-S PRT would serve to establish a standard  $Z$  table to satisfy our requirements. Because no known standard platinum  $Z$  function listing exists, two tables were established from NBS calibration data for a type P-S PRT which is used as a standard thermometer at Lewis. Table  $Z_I$  with base points at  $20.20^\circ$  K ( $T_1$ ) and  $77.40^\circ$  K ( $T_2$ ) lists  $Z_I$  values for every  $0.01^\circ$  K from  $10^\circ$  to  $92^\circ$  K. Table  $Z_{II}$  has base points at  $77.40^\circ$  K ( $T_1$ ) and  $273.15^\circ$  K ( $T_2$ ) with a  $Z_{II}$  value for every  $0.1^\circ$  K from  $70^\circ$  to  $600^\circ$  K. Figure 7 shows a plot of these  $Z$  functions.

Figure 14 shows that PRT types A-13, A-14, and A-15 are in close agreement with our standard  $Z_I$  temperature functions. All data are within  $\pm 0.04^\circ$  K for all PRT of the types tested. Also shown in figure 15 are typical single PRT deviations from the  $Z_I$  functions to demonstrate the scatter of our multipoint calibration. This data scatter is attributed to temperature gradients between PRT in our cryostat. In some cases the scatter exceeds the probable error in our resistance measurement, and all of these PRT had repeatable calibrations at  $20.20^\circ$  K and  $77.40^\circ$  K within instrumentation uncertainty of  $\pm 0.01^\circ$  K. This measurement error is pointed out because the matching of these PRT to our  $Z_I$  function is undoubtedly better than the data presented. However, further refinement to prove closer matching is unnecessary because the deviations are within our calibration accuracy requirements.

Figure 16 shows the maximum deviation from our  $Z_I$  function for 11 type F-16 PRT to be as high as  $0.84^\circ$  K. Also, agreement between PRT of F-16 type was only within tenths of a degree. Therefore, a modification of our  $Z_I$  table for this PRT type would still give unacceptable accuracies. Shown in figure 17 is a representative deviation from  $Z_I$  for a single F-16 PRT. These data for a poor quality PRT were included in this report to point out that not all PRT are of good enough quality to match a standard  $Z$  temperature function. A statistical sample of each type of PRT must first be multipoint calibrated to determine quality. However, with reference to table II, the poor quality of type F-16 was indicated even before multipoint calibration by its poor repeatability and high residual resistance.

$Z_{II}$  Matching,  $T_1 = 77.40^\circ$  K,  $T_2 = 273.15^\circ$  K. - Selected types of PRT also conform very well to standard  $Z_{II}$  functions based at  $77.40^\circ$  K ( $T_1$ ) and  $273.15^\circ$  K ( $T_2$ ). A typical type P-S thermometer will deviate no more than  $\pm 0.012^\circ$  K in the range of  $75^\circ$  to  $500^\circ$  K (fig. 18). The maximum deviation for 10 type A-15 PRT from  $77^\circ$  to  $273^\circ$  K is  $+0.035^\circ$  K (fig. 19). Temperature excursions more than  $20^\circ$  K beyond  $T_2$  result in poorer  $Z_{II}$  agreement and, hence, in greater errors (as much as  $0.45^\circ$  K at  $500^\circ$  K). Even this order of accuracy (0.1 percent of  $T$ ) is adequate for many applications and can be achieved with calibration at only two temperatures. For better accuracies at

temperatures above the ice point an additional  $Z$  table would be useful. It would be based at  $273.15^{\circ}$  K and at some higher temperature such as  $373.15^{\circ}$  or  $505.00^{\circ}$  K (freezing point of tin). For this range the Callendar equation (eq. (1)) is applicable if the constants are determined.

$Z_{III}$  Matching,  $T_1 = 4.20^{\circ}$  K,  $T_2 = 20.20^{\circ}$  K. - Certain types of high-resistance PRT are suitable for measuring temperatures with limited accuracy down to  $4.2^{\circ}$  K as suggested by Scott (ref. 12). This is accomplished with a  $Z_{III} - T$  curve (fig. 20) based at  $4.20^{\circ}$  K ( $T_1$ ) and  $20.20^{\circ}$  K ( $T_2$ ). The curve was developed from data for five PRT (type A-13) which were calibrated using two germanium standard thermometers to establish temperature. The germanium thermometers were calibrated by NBS to their 1965 Provisional temperature scale. Figure 21 shows the maximum deviations of the five A-13 PRT from their average  $Z_{III}$  function. Deviations as high as  $0.15^{\circ}$  K were obtained.

## CONCLUSIONS

Selective types of commercial platinum resistance thermometers (PRT) are available with high resistance. Yet, these PRT are compact, rugged, and comparable in quality to the well defined primary reference standard PRT. For PRT types of proven quality, fixed-point calibrations are adequate to define the resistance-temperature relation. Quality must first be established by multipoint calibration of a statistical sample of PRT of a given type. Fixed-point temperature calibrations (liquid hydrogen and nitrogen or hydrogen and oxygen) will yield probable calibration uncertainties within  $\pm 0.05^{\circ}$  K from  $20^{\circ}$  to  $92^{\circ}$  K. An additional measurement at the ice point ( $273.15^{\circ}$  K) will extend the calibration range to  $280^{\circ}$  K with equal accuracy.

Interpolation between calibration points is achieved by applying nondimensional resistance-difference ratios taken from NBS data for primary reference standard PRT. These ratios, referred to as  $Z$  functions, normalize resistance-temperature relations for PRT and also cancel residual resistances which are not temperature dependent.

For three types of commercial PRT as described in the foregoing text, we have demonstrated that resistance difference ratio  $Z$  functions based at  $20.20^{\circ}$  and at  $77.40^{\circ}$  K conform to those of a primary reference standard PRT to within  $\pm 0.04^{\circ}$  K. Equally accurate conformance holds for  $Z$  functions based at  $77.40^{\circ}$  and  $273.15^{\circ}$  K. This degree of uniformity in normalized resistance-temperature relations tends to simplify procedures for resistance-temperature data reduction.

In addition to the calibration conformance, the three types of PRT which were extensively tested also show other desirable characteristics indicative of good quality. Repeatability is within  $\pm 0.01^{\circ}$  K. High sensitivity is realizable. Also, high sensitivity in terms

of percentage change in resistance per  $^{\circ}\text{K}$  at very low temperatures suggests low residual resistance and freedom from strain. Self-heating in liquid nitrogen is on the order of  $0.03^{\circ}\text{K}$  per milliwatt. One failure out of 304 sensors with ordinary caution both in testing and in field usage indicates good reliability.

Temperatures as low as  $4.2^{\circ}\text{K}$  can be measured with PRT of the type and quality discussed. Calibrations of about five PRT of a given type, using one or more standard germanium thermometers to establish temperature, can be used to obtain a range of  $Z$  functions based at  $4.20^{\circ}$  and  $20.20^{\circ}\text{K}$ . Uncertainties are within  $\pm 0.2^{\circ}\text{K}$ .

Lewis Research Center,  
National Aeronautics and Space Administration,  
Cleveland, Ohio, November 28, 1967,  
128-31-06-36-22.

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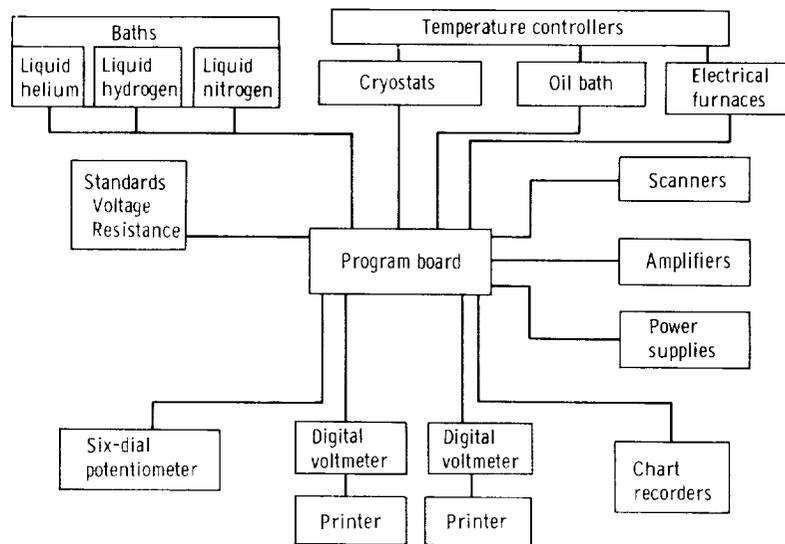
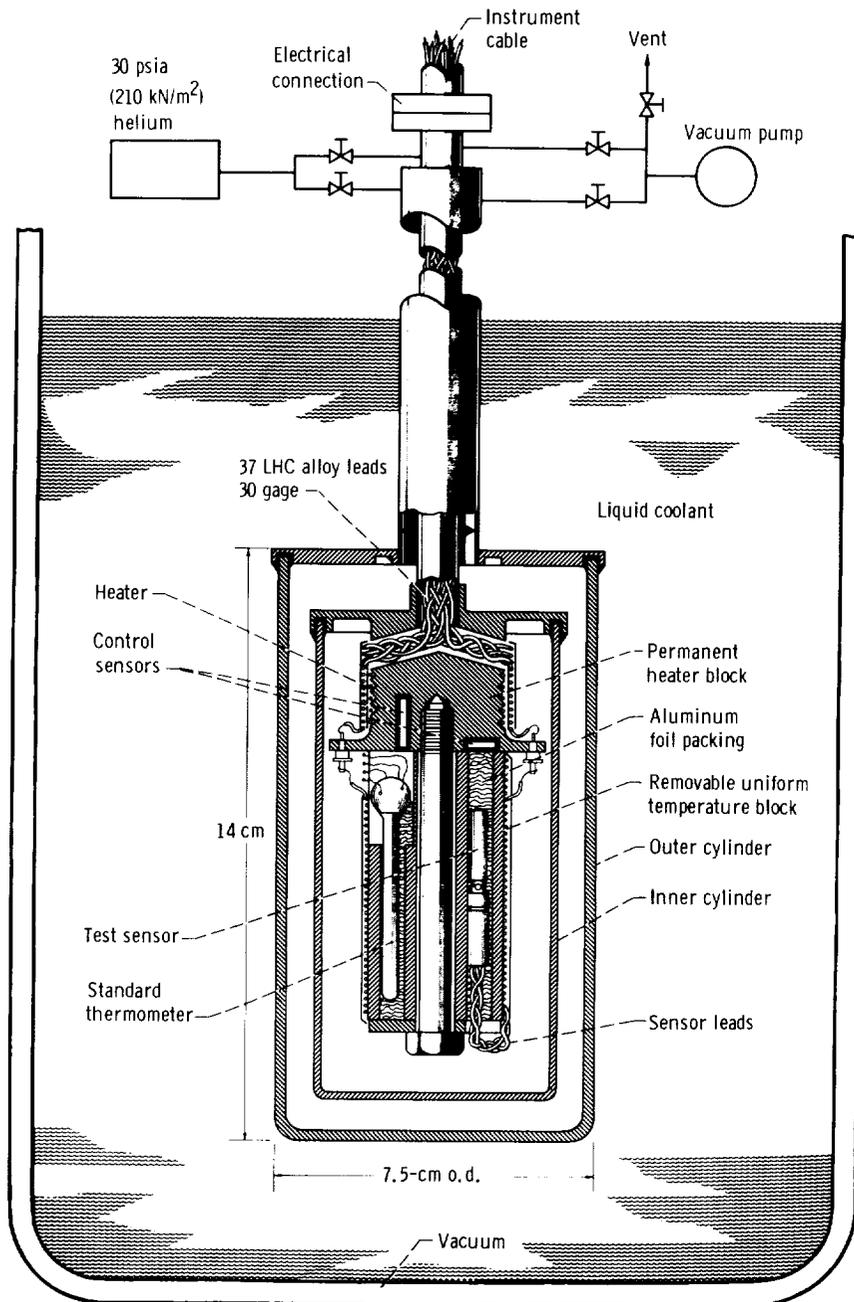


Figure 1. - Temperature calibration facility.



CD-9510

Figure 2. - Cryostat. Coolant, liquid helium, hydrogen or nitrogen.

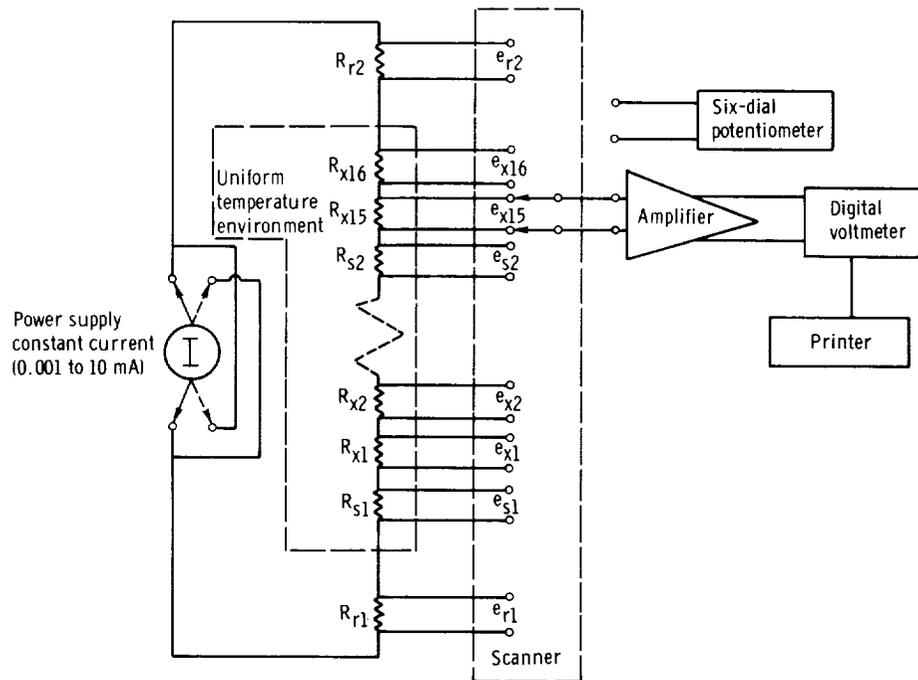


Figure 3. - Potential ratio resistance measuring circuit.

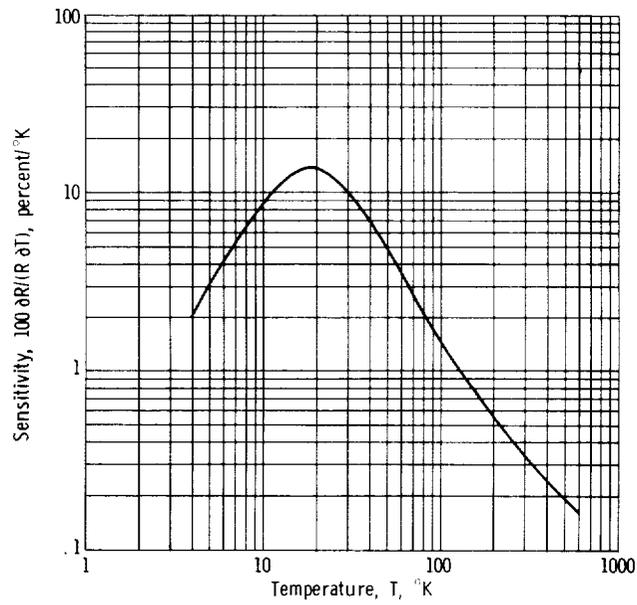


Figure 4. - Typical PRT sensitivity.

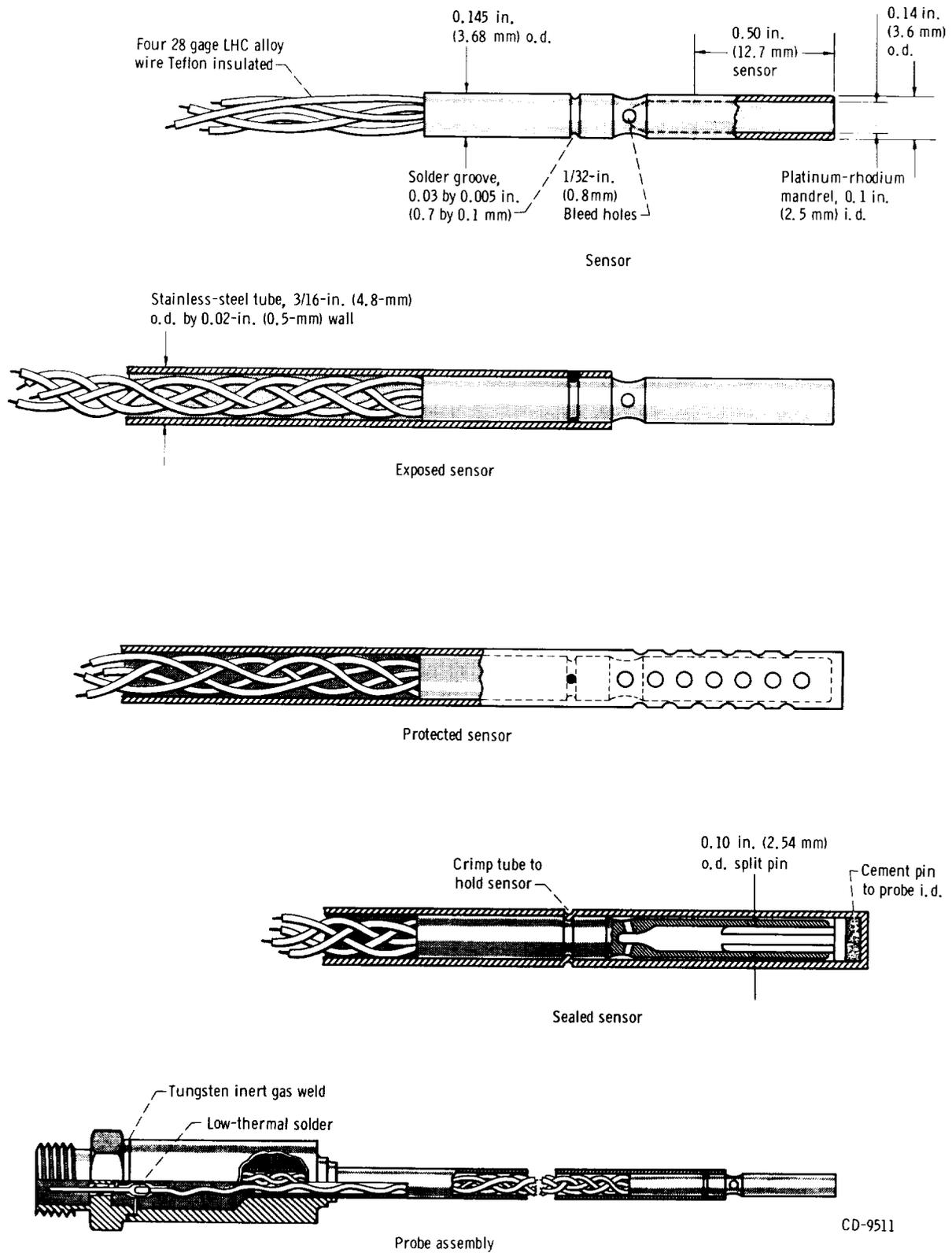


Figure 5. - Platinum resistance thermometer probes.

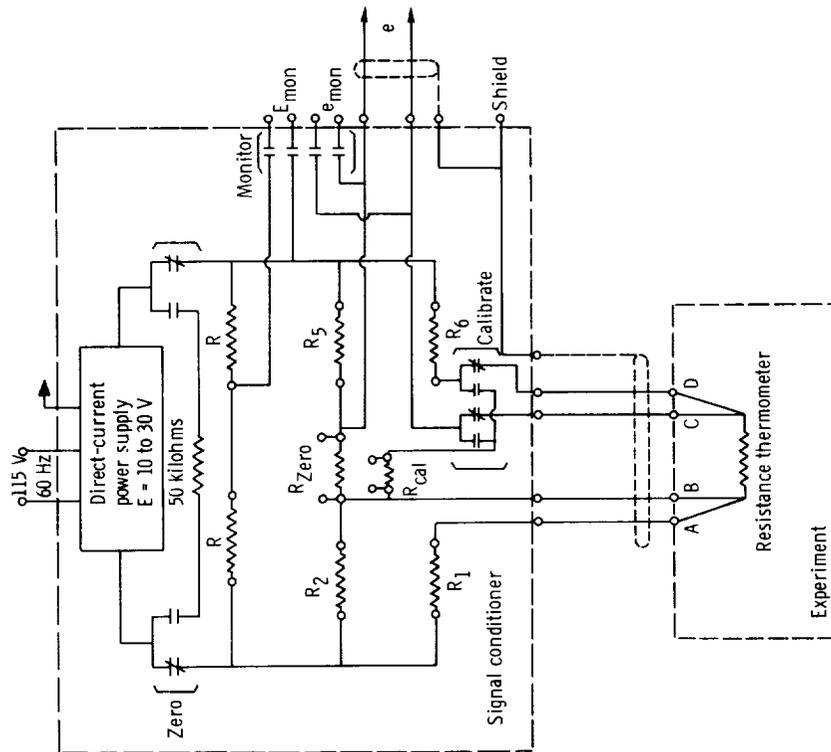


Figure 6. - Resistance thermometer and bridge signal conditioner measuring system.

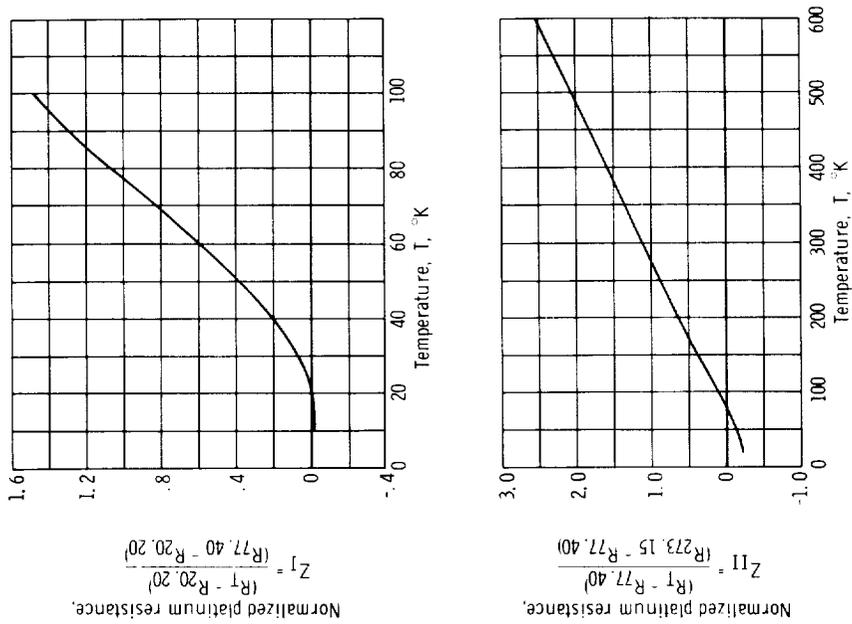


Figure 7. - Normalized platinum resistance as a function of temperature.

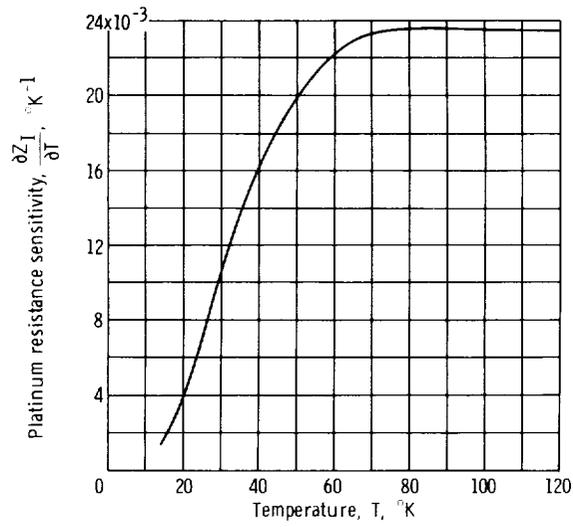


Figure 8. - Platinum resistance sensitivity.

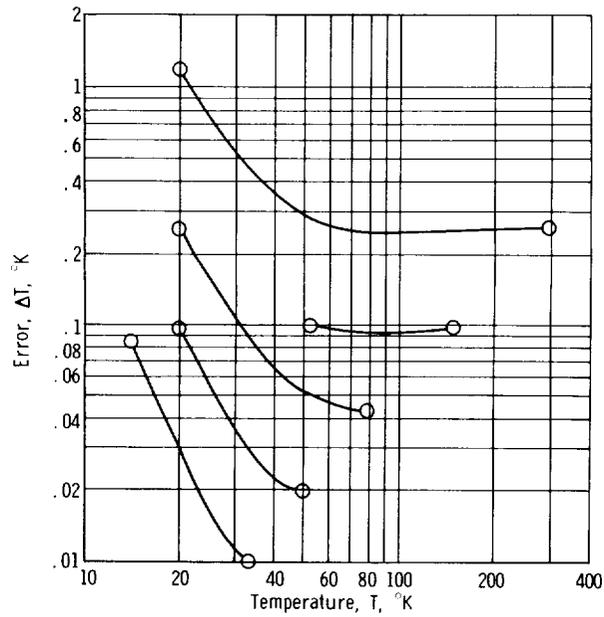


Figure 9. - Temperature error for signal error 0.1 percent of signal voltage at full scale for five typical temperature spans.

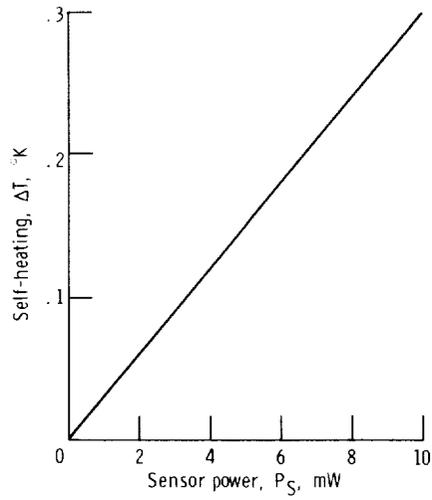


Figure 10. - Self-heating in liquid nitrogen. Five type A-15 platinum resistance thermometers.

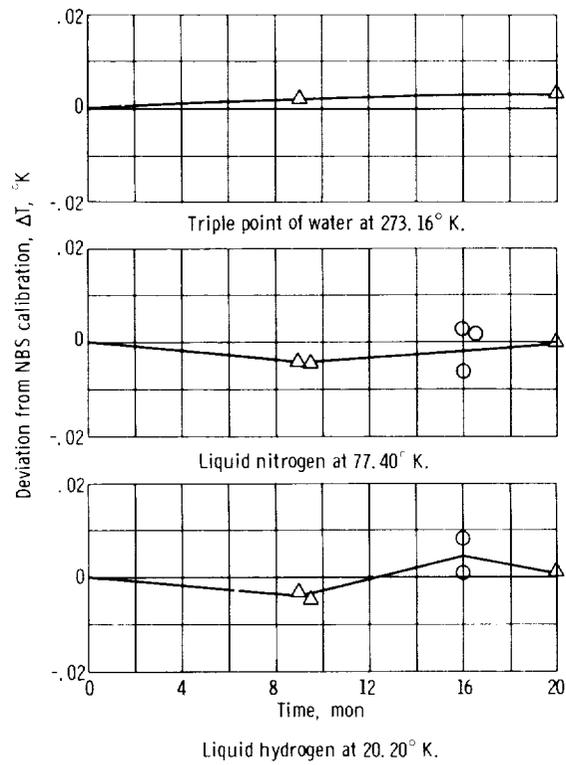


Figure 11. - Repeatability of one standard quality type P-S platinum resistance thermometer.

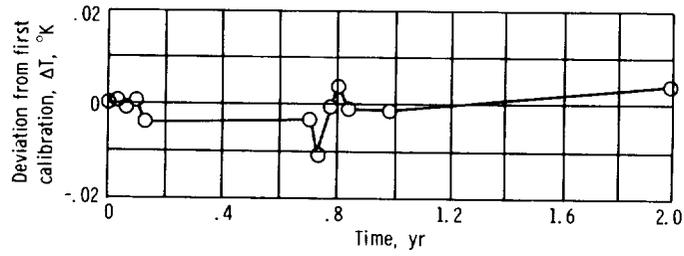


Figure 12. - Repeatability of one type A-1 platinum resistance thermometer at liquid-hydrogen temperature, (20.20° K).

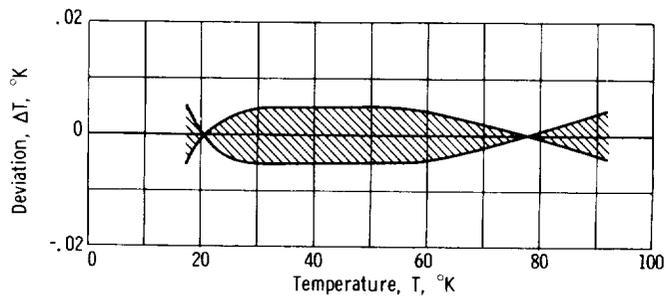


Figure 13. - Deviation of seven type P-S platinum resistance transducers from their average resistance difference function ( $Z_1$ ). Temperature at lower base point, 20.20° K; temperature at upper base point, 77.40° K.

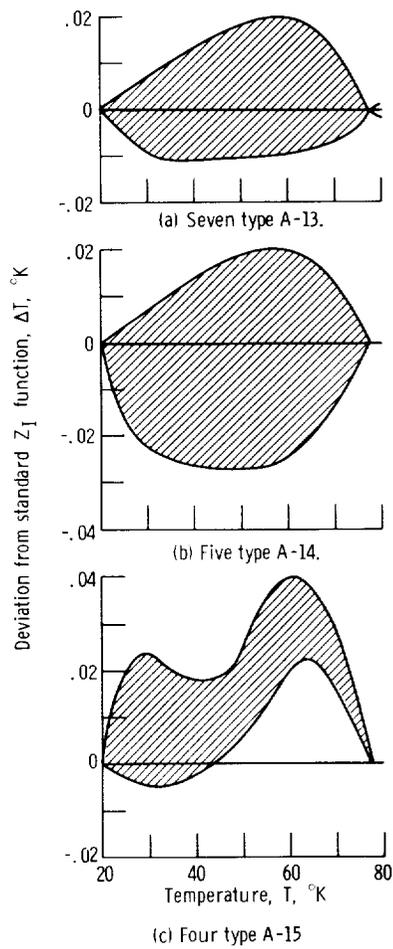


Figure 14. - Envelope of maximum deviation from resistance difference function ( $Z_1$ ) for different platinum resistance thermometers.

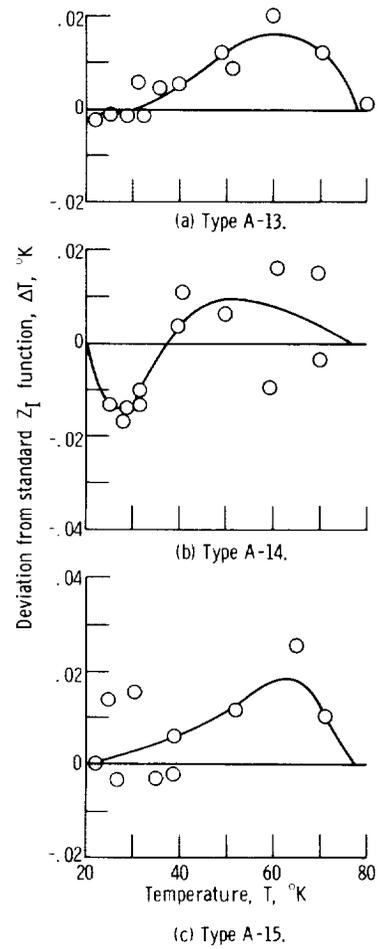


Figure 15. - Representative deviation from resistance difference function ( $Z_1$ ) for different single platinum resistance thermometers.

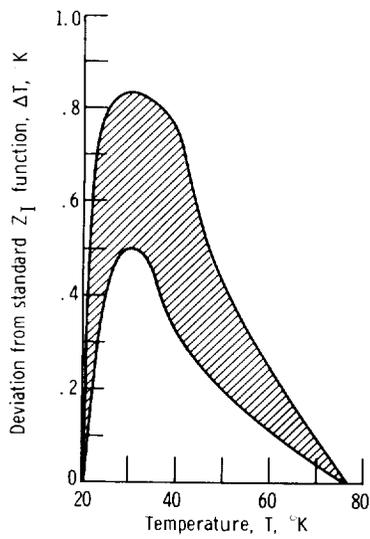


Figure 16. - Envelope of maximum deviations from resistance difference function ( $Z_T$ ) for 11, type F-16 platinum resistance thermometers.

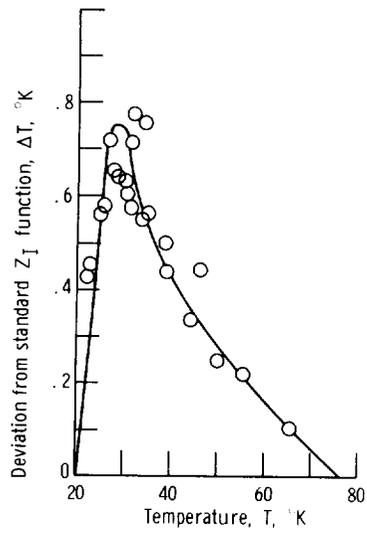


Figure 17. - Representative deviation from resistance difference function ( $Z_T$ ) for single type F-16 platinum resistance thermometer.

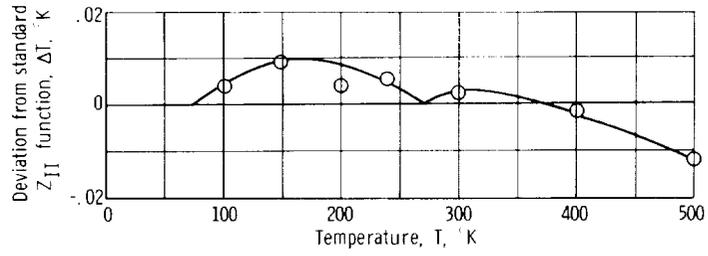


Figure 18. - Representative deviation from  $Z_{II}$  for single type P-S platinum resistance thermometer.

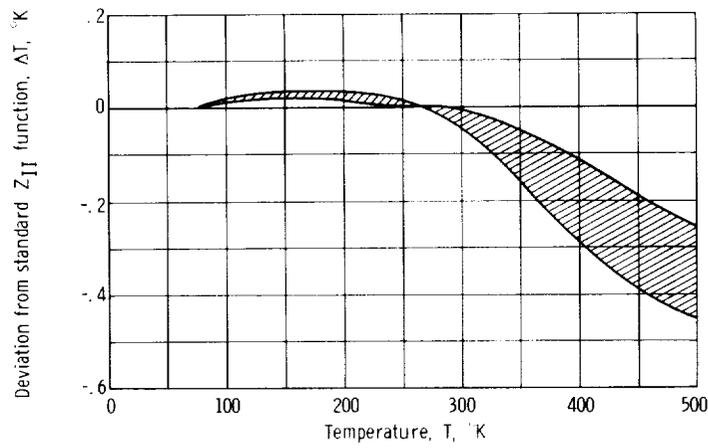


Figure 19. - Envelope of maximum deviations from resistance difference function ( $Z_{II}$ ) for 10 type A-15 platinum resistance thermometers.

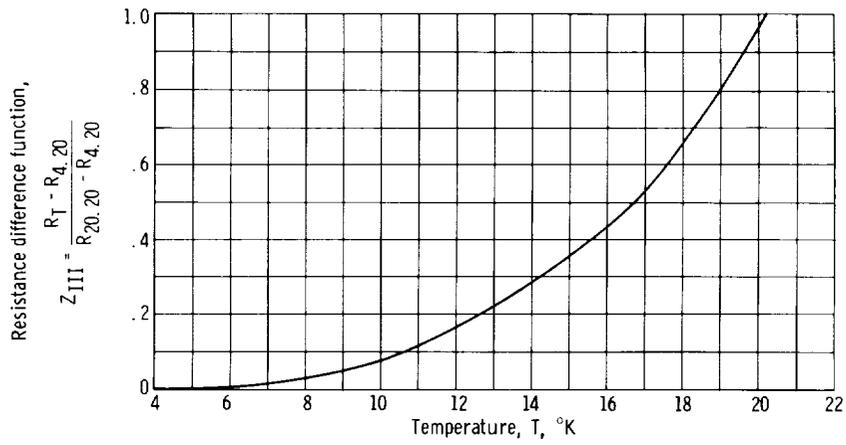


Figure 20. - Resistance difference function against temperature.

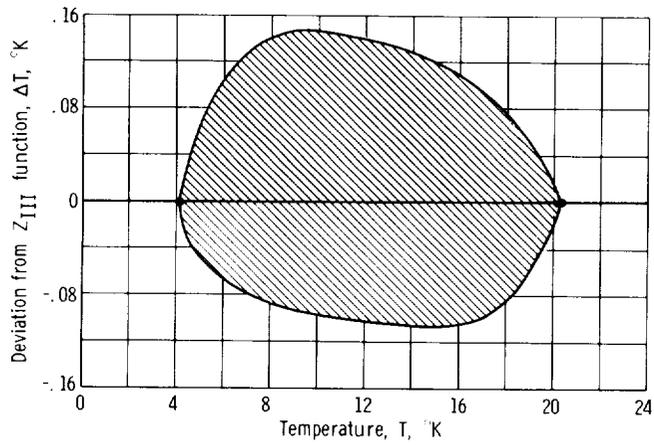


Figure 21. - Envelope of maximum deviations for five type A-13 platinum resistance thermometers from their average resistance difference function ( $Z_{III}$ ).

